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Strontium—Uses, Supply, and Technology

UNITED STATES DEPARTMENT OF THE INTERIOR

Information Circular 9213

Strontium—Uses, Supply, and Technology

By Joyce A. Ober

UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

BUREAU OF MINES
T S Ary, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	st	short ton
h	hour	st/yr	short ton per year
lb	pound	yr	year

STRONTIUM—USES, SUPPLY, AND TECHNOLOGY

By Joyce A. Ober[1]

ABSTRACT

This Bureau of Mines report attempts to present a complete picture of the state of the international strontium industry, including end uses, world resources, chemical production, supply-demand relationships, and Government programs.

Strontium is produced from an ore, celestite, which is found in several countries; dominant producers are Mexico, Spain, and Turkey. The United States does not mine celestite domestically, but nearly 100% of its imports come from Mexico. Because of the good relationship between the two countries, and their close geograhic proximity, there is little concern over the stability of supply for the foreseeable future. Major end uses for strontium include color television faceplate glass, permanent ceramic magnets, and pyrotechnics.

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INTRODUCTION

Recent advances in materials technology have changed the way scientists and engineers think about the future. Manufacturers are no longer as reliant on traditional materials for their processes. In many instances new developments have rendered existing technology obsolete. Advanced or "high-tech" materials have replaced the old standards in many applications. Although the meanings of these terms are obscure at best, attempts have been made to define what makes a material advanced. The Bureau of Mines is currently using the following definition (*31*)[2] when referring to advanced materials:

> Advanced materials are those developed over the past 30 years or so, and being developed at the present, that exhibit greater strength/density ratios, greater hardness, and/or one or more superior thermal, electrical, optical, or chemical properties, when compared with traditional materials. Advanced metals, ceramics, and polymers, including composites of these, offer the promise of decreased energy consumption, better performance at lower cost, and less dependence on imports of strategic and critical materials. New electronic, magnetic, optical, and chemical devices, engineered at the molecular level, are resulting in a revolution in communications, data analysis, medical technology, and industrial processing that promises dramatic changes in manufacturing and human life style.
>
> Further qualifications are necessary to distinguish the new advanced materials from former advanced materials:
>
> • They may require advanced and sophisticated processing to attain the required purity levels and physical characteristics needed for use by high-technology industries.
>
> • Fabrication technology is, in many cases, the major technical barrier to commercial application. Application requires redesign, retooling, and new process development to assure uniformity, high yield, and reliability. Now, more than ever before, research and development personnel are required to participate in the pilot plant and production stages.
>
> • There is an increased need for materials producers and product manufacturers to work together from the design stage through the manufacturing stage. In some cases, the material may be developed to satisfy design demands and, in other cases, the design must be adapted to the properties of the material, so that an iterative process takes place to produce optimum properties and performance.

Because of the large number of advanced materials included in the design of new and emerging weapons systems and other military equipment, the Department of Defense (DOD) identified a list of high-technology or advanced materials upon which to focus new studies and policies. DOD concerns about these materials include necessary raw materials for producing the advanced materials, technology needed for this production, and availability of raw materials for production. The list of 22 materials of special interest to DOD and described as "high-tech" metals follows:

Indium	Bismuth
Gallium	Mercury
Rare-earth metals	Selenium
Tellurium	Beryllium
Platinum-group metals	Ruthenium
High-purity chromium	Scandium
Hafnium	Zirconium
High-purity manganese	Rhodium
Metal-matrix composites	Osmium
Rhenium	Cesium
Yttrium	Strontium

A companion list contains categories of materials and processes in which DOD is also interested, as follows:

- Carbon and ceramic fibers
- Compound semiconductor materials
- Large-diameter float-zone silicon material
- Advanced structural (high-temperature) ceramics
- Piezoelectric and other transducer and sensor devices
- Semiconductor injection lasers
- Diamond films for structural purposes and electronic applications
- High-critical-temperature superconductors based on ceramic composites
- Large-diameter, microelectronic-circuit-quality Czochralski silicon wafers
- Magnetic and optical recording media

The Bureau has traditionally aided DOD in maintaining up-to-date information and conducting necessary research on defense-related materials including traditional and advanced materials and has begun compiling special reports dealing with the materials listed. Thus far reports have been prepared on indium, gallium, and float-zone silicon material; reports on the other materials on the list may be published in the future. The present report surveys important strontium end uses and possible future developments; also included are supply aspects, resource information, and recovery technology.

Strontium is used in the form of chemical compounds, usually produced from the mineral celestite. The United States is presently 100% dependent on imported strontium minerals, most of which are imported from Mexico. Although possible disruptions in supply are always a concern when the United States is dependent on foreign sources for any material, and especially when the material is used in military applications, relations with Mexico are such that the supply of strontium is fairly well assured for the foreseeable future and under foreseeable circumstances.

[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

STRONTIUM COMPOUNDS AND THEIR END USES

Almost everyone living in the United States has some strontium in their home. Approximately 2 lb of strontium oxide (SrO) are contained in every color television set. Many refrigerators' door seals are strontium ferrite magnets, and most small motors and loudspeakers utilize strontium magnets. Strontium end uses range from common, everyday materials to possibilities as sophisticated advanced materials.

Figure 1 represents an estimated distribution of primary strontium compounds by end use. Close to 75% of all strontium consumed is in ceramics and glass manufacture, primarily in color television faceplate glass and ceramic ferrite magnets, and to a smaller degree in other ceramic and glass applications. Table 1 shows how end use distribution has fluctuated over the past 10 yr. It has only been in the past 20 yr that color television production has become the major consumer of strontium.

Special end uses of strontium compounds have been developed because of unique properties that they possess. Table 2 shows some physical properties of the more common strontium compounds. In most cases each end use takes advantage of a property that is uniquely appropriate for that specific application.

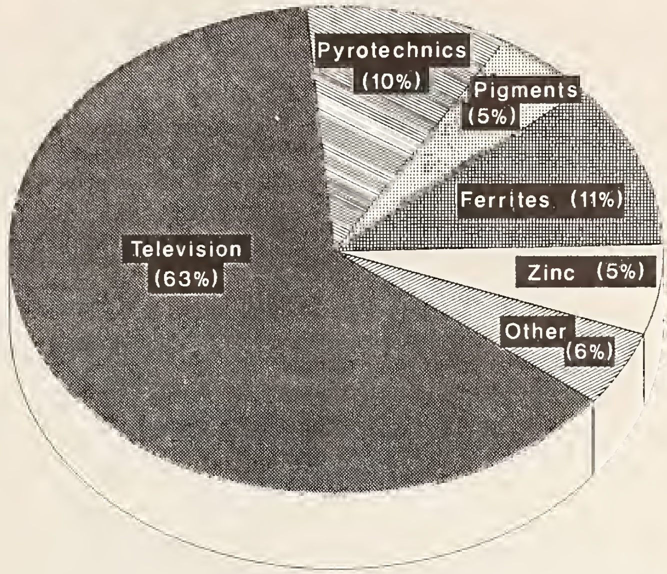

FIGURE 1.—Estimated end use distribution of strontium compounds, based on contained strontium; 1987 consumption—19,100 tons.

TABLE 1.—U.S. estimated distribution of primary strontium compounds, by end use, 1978-87
(Percent)

End use	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Electrolytic production of zinc	3	7	5	4	3	3	6	6	6	5
Ferrite ceramic magnets	5	10	5	5	7	9	11	12	11	11
Pigments and fillers	NA	4	4	4	4	4	8	8	7	5
Pyrotechnics and signals	17	16	12	15	15	14	14	15	10	10
Television picture tubes	66	57	67	65	62	64	53	52	60	63
Other	NA	6	7	7	9	6	8	7	6	6
Total	91	100	100	100	100	100	100	100	100	100

NA Not available.

TABLE 2.—Physical properties and uses of selected strontium compounds

Compound	Chemical formula	Molecular weight	Specific gravity	Melting point, °C	Primary uses
Carbonate	$SrCO_3$	147.63	3.70	1,497	Ceramics and glass.
Chloride	$SrCl_2$	158.53	3.052	873	Desensitizing toothpaste.
Chromate	$SrCrO_4$	203.61	3.895	NAp	Anticorrosive paint.
Nitrate	$Sr(NO_3)_2$	211.63	2.986	570	Pyrotechnics.
Oxalate	$SrC_2O_4 \cdot H_2O$	193.64	NAp	NAp	Do.
Oxide	SrO	103.62	4.70	2,430	Ceramics and glass.
Peroxide	SrO_2	119.62	4.56	(1)	Pyrotechnics.
Sulfate	$SrSO_4$	183.68	3.96	1,605	As celestite, raw material for all other compounds.
Sulfide	SrS	119.68	3.70	2,000	Intermediate material in conversion of celestite to carbonate.

NAp Not applicable. [1] Decomposes on heating.

TELEVISION FACEPLATE GLASS

All color televisions and other devices containing color cathode ray tubes (CRT's) sold in the United States are required by law to contain strontium in the faceplate glass of the picture tube to block X-rays; this is the largest end use for strontium compounds worldwide. Strontium blocks x-rays better than barium, which was previously used, and although lead is a better X-ray barrier than strontium, it causes a browning of the glass, which makes its use undesirable (*43*). Televisions produced and sold in Western Europe do not require strontium because they use lower power; barium is capable of blocking the X-ray emissions at the lower power level, at a lower cost (*28*, p. 41).

Major manufacturers of television picture tube glass and other forms of color CRT's incorporate about 8% by weight SrO in their glass faceplate material. The strontium is added to the glass melt in the form of strontium carbonate ($SrCO_3$), which is converted to SrO during processing (*23*). SrO is the dominant alkaline earth oxide present along with alkali metal oxides in picture tube glass. In addition to blocking X-rays, the strontium improves the brilliance of the glass and improves the quality of the picture. The rear section of the picture tube or funnel is not adversely affected by the browning caused by lead, and so may not contain strontium, but some manufacturers use strontium in this part of the tube also.

Trends in television production show a shift to larger, flatter, tubes that require thicker glass, and thus more strontium (*43*). Although the television industry in the United States is considered mature, there is a continuing demand for replacement televisions and additional sets in large numbers of households. The trend to personal computers and sophisticated, computerized instrumentation is increasing the demand for strontium in color monitors for these devices. Recent exchange rates have contributed to a trend for U.S. television manufacturers to increase domestic production rather than buying sets produced in Japan and the Far East (*4, 27*).

Other devices that contain strontium to shield X-ray emissions are radar screens, sonar screens, and instruments used in guidance and control in modern military aircraft, naval vessels, and weapons systems.

PYROTECHNICS

One of the most consistent and continuing uses for strontium has been in pyrotechnic devices. During this century, very little change has occurred in the formulas used in pyrotechnics to produce specific colored flames. Strontium burns with a brilliant red flame, and no other material has been found to be better in this application. The red light is emitted at a specified wavelength, unique to strontium compounds. Other compounds, some containing lithium, emit a similar red color, but other properties make their utilization less attractive. Lithium compounds are hygroscopic, absorbing moisture from the air and forming wet masses that are hard to burn (*12*, p. 33).

The strontium compound used most frequently in pyrotechnic devices is strontium nitrate [$Sr(NO_3)_2$]. Some strontium compounds are slightly hygroscopic, but $Sr(NO_3)_2$ takes on very little water and imparts the desired brilliant red. Other strontium compounds are used in pyrotechnic applications, such as $SrCO_3$, strontium oxalate ($SrC_2O_4 \cdot H_2O$), strontium sulfate ($SrSO_4$), and strontium chlorate ($SrClO_3$), but $Sr(NO_3)_2$ is used in significantly larger quantities than any of these (*6*).

Pyrotechnic devices are used in military and nonmilitary applications. Military pyrotechnic applications that contain strontium include tracer ammunition, military flares, and marine distress signals. Nonmilitary applications include warning devices and fireworks. The Coast Guard requires certain classes of water craft to carry specific types of red signalling devices. Vehicles operated for interstate commerce are required by law to carry certain warning devices, which frequently include railroad fusees containing strontium. As the name indicates, fusees are also used as warning devices on trains as well as by police and firefighters (*17*).

PERMANENT CERAMIC MAGNETS

Permanent ceramic magnets are another large end use for strontium compounds, in the form of strontium ferrite (usually $SrFe_{12}O_{19}$ or $SrO{\bullet}6Fe_2O_3$). These magnets, originally used primarily as magnetic closures for refrigerator doors, are now used extensively in small direct current (dc) motors, especially in automotive applications such as windshield wiper motors, and in loudspeakers, other electronic equipment, toys, and magnetically attached decorative items (*2*).

Strontium ferrites are used in permanent ceramic magnets because they have high coercive force and high thermal and electrical resistivity and are chemically inert (*33*). This means that they retain their magnetism well, are not adversely affected by electrical currents or high temperatures, and do not react with most chemical solvents. They also have a high degree of spontaneous magnetism and anisotropy. Spontaneous magnetism means that materials exhibit magnetic properties in the absence of an outside force, and anisotropy indicates the magnetization occurs along a specific direction, creating strong positive and negative poles. Anisotropy is enhanced by orienting tiny individual crystals with a strong magnetic field during the production process, creating strong polarity in the magnets (*2*). Other properties that make the strontium magnets more attractive for specific applications are their resistance to demagnetization and their lower density, which makes them more desirable in applications where weight is a factor.

Strontium ferrite magnets are generally prepared by mixing $SrCO_3$, iron oxide, and crystal growth inhibitors and presintering at 1,000° to 1,300° C. The preintered material is then ground to the desired particle size, mixed with a binder, and pressed into rigid, semirigid, or flexible bonded permanent magnets (*25*). These steps are altered according to the final application for the magnet. Ferrite magnets can be custom-formulated to achieve optimum properties for specific applications.

Barium or lead can replace the strontium in ferrite magnets, but strontium ferrites possess the best combination of properties necessary for superior magnets.

ELECTROLYTIC PRODUCTION OF ZINC

Strontium is used to remove lead impurities during the electrolytic production of zinc. Zinc used in die-casting alloys is required to contain less than 0.003% lead. Addition of $SrCO_3$ in sulfuric acid (H_2SO_4) to the electrolyte reduces the lead content of the electrolyte and of the zinc that is deposited on the cathode.

Tests have shown that the lead is incorporated into the $SrSO_4$ crystal formed during the reaction of $SrCO_3$ with H_2SO_4. The precipitates formed during the reaction fall from the solution, removing the lead (*3*). This occurs because of the similarities in structure and reactivity between lead and strontium.

PAINT PIGMENTS

The addition of strontium chromate ($SrCrO_4$) to paint creates a coating that is resistant to corrosion. It is an effective coating for aluminum, most notably on aircraft fuselages and ships (*28*, p. 67). These paints are used to some degree on aluminum packaging to prevent package corrosion. The nitrate and chloride contents of $SrCrO_4$ paint pigment are very strictly controlled to prevent corrosion.

Ground celestite is sometimes used as a filler and extender in paints, especially in Europe (*28*, p. 67).

Strontium sulfide (SrS) is used as the active ingredient in some luminescent paints. SrS can also be used as the luminous pigment in phosphorescent paints. In a fine crystalline powder luminous SrS exhibits exceptional light-bearing qualities and length of afterglow without the dangers inherent in the radium coatings formerly used. Although there is little or no consumption of strontium in this application currently, this is a good example of strontium's unique attributes (*1*).

STRONTIUM METAL AND ALLOYS

In the metallic form strontium is a silvery white metal that oxidizes quickly in air to a yellowish color. It decomposes water to form SrO and hydrogen and is soluble in acid, alcohol, and liquid ammonia. The metal is reactive and, if finely divided, will ignite spontaneously in air. Sr^{90} is a radioactive component of nuclear fallout which because of its 28-yr half-life presents a health hazard (*45*, p. B-31).

Consumption of metallic strontium is still a very limited factor in total strontium consumption. Small amounts of strontium are added to molten aluminum to improve its castability, making it much more suitable for casting items that have been traditionally made from steel. The addition of strontium to the melt improves the machinability of the casting (*35*) and is one of the modification techniques that have made it practical to use cast aluminum parts in the automotive industry. The reduction in car weight achieved by using cast aluminum parts instead of steel helps to improve energy efficiency.

Strontium metal is produced by electrolysis of fused strontium chloride ($SrCl_2$) mixed with potassium chloride or by reducing SrO with aluminum in a vacuum at a temperature at which strontium is distilled, i.e., over 1,384° C (*29*, p. 27).

SUPERCONDUCTORS

Some superconductor research has indicated that one component of high-temperature superconductors could eventually be SrO. Mixtures of SrO with other metallic oxides exhibit superconducting properties. This research is still in its early stages, and although it has received much media attention, it could be a long time before these materials achieve practical applications and commercial success. Very high purity SrO is believed to be essential to the stability of these materials, but their production is currently done on an extremely small scale (*44*).

OTHER USES

There are a number of other strontium end uses, although at present they consume only small amounts of strontium and strontium compounds. As mentioned previously, the presence of strontium in glass improves its brilliance. Strontium also improves the quality of certain ceramic glazes, without introducing the toxicity that may be present in glazes containing lead or barium (*29*, p. 9). One high-tech strontium ceramic is strontium titanate, used as substrate material for some semiconductors and in some optical and piezoelectric applications.

$SrCl_2$ is used in toothpaste for sensitive teeth. For this application impurities must be strictly controlled; limits for some are in the parts per million range (*12*).

Strontium phosphate ($SrHPO_4$) is used in the manufacture of fluorescent lights, and the entire range of strontium chemicals is used in analytical chemistry laboratories (*12*, p. 35).

WORLD RESOURCES

Strontium occurs commonly in nature, averaging 0.034% of all igneous rock, but only two minerals, celestite and strontianite, contain strontium in sufficient quanitities to make its recovery practical. Celestite consists primarily of $SrSO_4$, and strontianite consists primarily of $SrCO_3$. Of the two, only celestite has been found in deposits of sufficient size to make development of mining facilities currently attractive (*29*, pp. 13-14). Strontianite would be more useful because strontium is used most commonly in the carbonate form, but few deposits have been discovered suitable for development (*7*). In almost all instances, celestite deposits occur in remote, nondeveloped locations far from population centers but where inexpensive labor is available for mining.

Huge deposits of high-grade celestite have been discovered throughout the world. Strontium often occurs along with barium and calcium, two elements with very similar properties, making separation difficult. Because removing many impurities from celestite is difficult and energy intensive, current strontium chemical producers require material to contain at least 90% $SrSO_4$. Most currently operating celestite facilities can produce sufficient supplies with only minimal processing necessary to achieve acceptable specifications. Hand sorting and some washing are all that are necessary at many strontium mines; only a few operations use froth flotation or gravity separation to beneficiate their ore.

Both strontium minerals occur primarily in sedimentary deposits, often in close proximity to limestone and barite. Strontium does occur in igneous rocks, but not in high enough concentrations to make them an acceptable source (*7*).

Detailed information on most world resources is not readily available. Many of the large deposits are in remote, sparsely inhabited areas, and very little formal exploration has been done. Other deposits may be well identified, but are located in countries from which specific mineral information is not easily obtained. Table 3 indicates countries where strontium deposits are known to exist, as well as countries that produce strontium carbonate. Table 4 shows recent production figures of strontium minerals from these mines.

TABLE 3.—Estimated celestite resources and strontium carbonate production capacities worldwide
(Short tons)

Country	Estimated resource[1]	Estimated annual strontium carbonate capacity
Algeria[2]	1,000,000	0
Argentina	NA	0
Australia	NA	0
Canada	1,000,000	0
China	NA	2,000
Cyprus	220,000	0
Federal Republic of Germany	0	16,500
India[2]	750,000	0
Iran	2,000,000	0
Italy	NA	0
Japan	0	34,000
Madagascar	NA	0
Mexico	2,000,000	21,000
Pakistan	750,000	0
Republic of Korea[3]	0	55,000
Spain	2,200,000	8,800
Turkey	2,000,000	0
United Kingdom[2]	330,000	NA
United States[2]	1,500,000	11,000
U.S.S.R.	NA	2,000
Total	13,750,000	150,300

NA Not available.
[1] Resource is defined as a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.
[2] Reports indicate resource size, but actual resources are questionable.
[3] Capacities of proposed production facilities.

Sources: U.S. Department of State, Roskill Information Services, Ltd., Industrial Minerals, U.S. Bureau of Mines.

TABLE 4.—World production of strontium minerals, 1977-87
(Short tons)

Country[1]	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986[p]	1987[e]
Algeria	5,622	6,418	3,200	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000
Argentina	925	1,317	134	295	342	855	742	441	1,084	1,249	1,100
Cyprus	0	0	0	0	0	0	0	0	1,543	8,119	8,000
Iran	11,000	16,500	9,700	6,100	5,500	33,070	24,251	23,149	27,558	24,251	24,250
Italy	770	402	1,866	1,161	7,382	3,607	456	2,866	5,083	5,144	195
Mexico	50,302	36,563	43,562	44,931	45,574	34,917	41,343	35,264	33,601	26,774	68,597
Pakistan	402	239	747	276	317	513	149	622	791	1,099	1,100
Spain	8,300	15,432	19,842	20,944	39,683	38,470	38,000	29,760	46,848	38,030	38,000
Turkey[e]	18,300	19,300	19,800	17,600	16,500	16,500	42,808	38,600	38,600	38,600	38,600
United Kingdom	5,622	4,740	6,724	7,386	16,000	19,800	13,340	17,750	25,353	15,543	16,500
Total	101,243	100,911	105,575	104,693	137,298	153,732	167,089	154,452	186,461	164,809	202,342

[e] Estimated. [p] Preliminary.
[1] In addition to countries listed, China, the German Democratic Republic, Poland, and the U.S.S.R. produce strontium minerals, but output is not reported quantitatively and available information is inadequate for formulation of reliable estimates of output levels.

RECOVERY TECHNOLOGY

Large, high-grade deposits have been identified that require little or no beneficiation. The beneficiation that is necessary can usually can be done by hand sorting or simple washing procedures. For this reason there has been little development of more sophisticated, complicated, and ultimately more expensive techniques for beneficiation.

Recovery technology for strontium and strontium compounds has remained virtually unchanged for most of this century. Two basic methods for converting celestite to $SrCO_3$, the most commonly used form of strontium, have been used for many years, with differences occurring in individual plants to adapt the processes to specific local problems. In most cases these adaptations are considered proprietary by the companies involved.

The black ash method and the soda ash method are the two basic recovery techniques. The black ash method, known alternatively as the calcining method, produces chemical-grade $SrCO_3$, which is at least 98% $SrCO_3$. The soda ash, or direct-conversion, method produces technical-grade $SrCO_3$, which contains at least 95% $SrCO_3$.

The black ash method received its name because the first step in the procedure involves mixing the crushed and screened celestite with powdered coal, making a black mixture. The mixture is then reduced at about 1,100° C, expelling oxygen in the form of carbon dioxide (CO_2) from the insoluble $SrSO_4$ to form water-soluble SrS. The major U.S. producer calls this method the white ash method, because at this point the calcined material is light in color.

SrS is dissolved in water, and the resulting solution is filtered. CO_2 is then passed through the solution, or soda ash (Na_2CO_3) is added. Either compound provides the carbon and oxygen necessary for $SrCO_3$ to form and precipitate from the solution. The precipitated $SrCO_3$ is then removed from the solution by filtering and is dried, ground, and packaged. The sulfur released in the process is recovered either as elemental sulfur or in other byproduct sulfur compounds.

In the soda ash method, ground celestite is washed, and most of the water is removed. The thickened mixture is then mixed with soda ash and treated with steam for 1 to 3 h. During this reaction time celestite and soda ash react to form $SrCO_3$ and sodium sulfate (Na_2SO_4). Na_2SO_4 is soluble, making it possible to separate the insoluble $SrCO_3$ by centrifuging.

While the soda ash method is a simpler process, as figure 2 shows, it is not necessarily the preferred method of recovery because of the lower grade of the product. The black ash method seems to be the most common method of $SrCO_3$ production.

$SrCO_3$ is the intermediate compound in the production of most other strontium compounds. For most applications, chemical-grade $SrCO_3$, which is greater than 98% pure, can be used without further purification. Either chemical-grade or technical-grade $SrCO_3$, greater than 95% pure, is adequate for transformation to other strontium compounds, and in the conversion processes further purification occurs. In some instances higher degrees of $SrCO_3$ purity are required, with special emphasis placed on eliminating contamination from particular elements.

$Sr(NO_3)_2$, the second most important strontium chemical, is produced through the reaction of $SrCO_3$ with nitric acid (HNO_3). Other strontium chemicals are produced through similar procedures of reacting $SrCO_3$ with the acid appropriate for the desired result. Some of the acids used are bromic, hydrochloric, oxalic, stearic, and tartaric (*29*, pp. 26-27).

Strontium ferrite magnets are generally prepared by mixing $SrCO_3$, iron oxide, and crystal growth inhibitors and presintering at 1,000° to 1,300° (*25*, pp. 889-890). Strontium titanate ($SrTiO_3$) is formed by reacting a mixture of high-purity $SrCO_3$ and titanium dioxide (TiO_2) at 2,000° to 2,200° C for several hours (*12*, p. 35).

Strontium metal can be produced in two ways. The more common method is through the thermal reduction of SrO and aluminum metal, subsequent distillation under high vacuum, and condensation of metallic strontium on a cooled plate. The other method is electrolysis of a fused bath of $SrCl_2$ and ammonium chloride or potassium chloride (*29*, pp. 27-28).

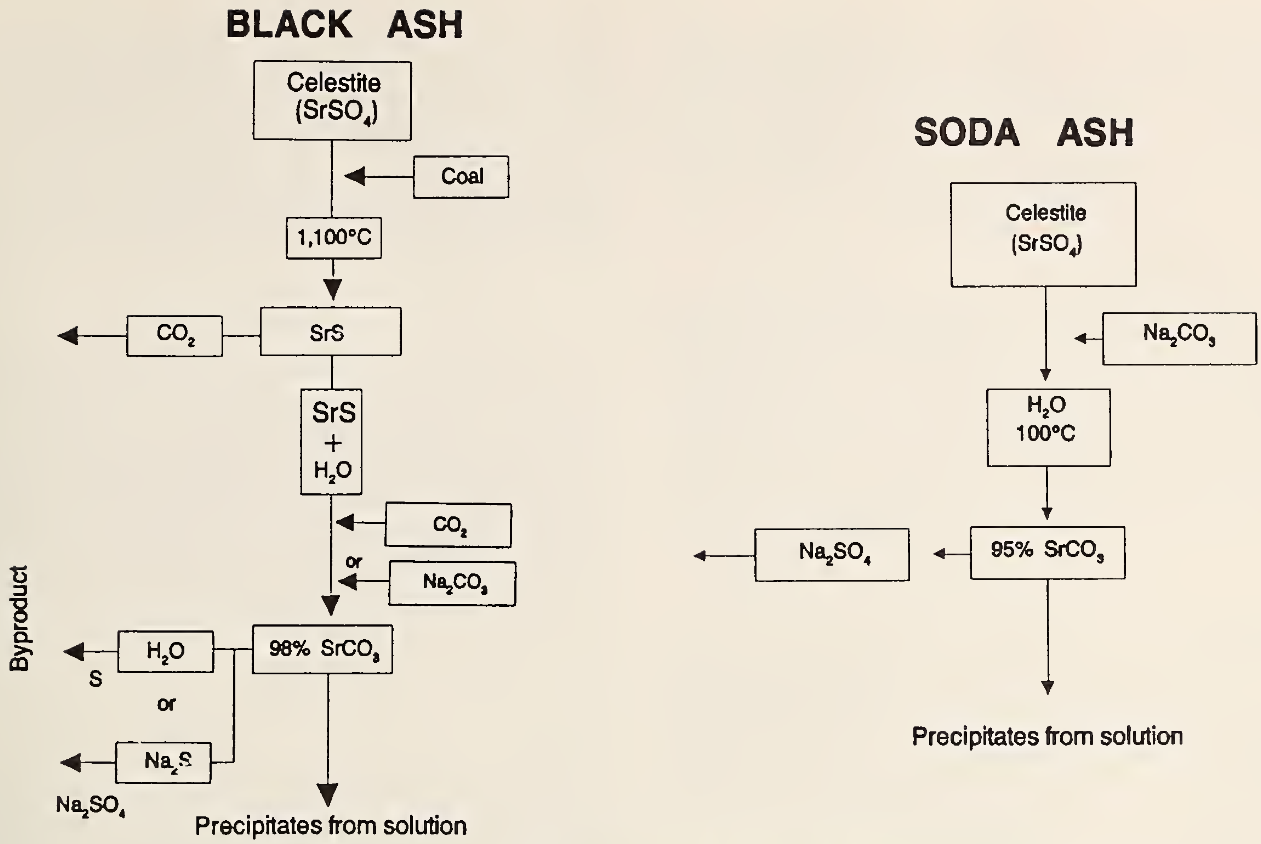

FIGURE 2.—Simplified flowchart of two methods for strontium carbonate production.

STRUCTURE OF THE STRONTIUM MINING AND CHEMICAL COMPOUND INDUSTRIES

Celestite is the only strontium mineral that is commercially available. Details on celestite deposits are listed below, by country. Also included is a list of strontium chemical producers that consume strontium minerals to produce $SrCO_3$ and other strontium compounds.

$SrCO_3$ is the most important of the various strontium compounds because it is the product that is consumed in most end use applications as well as being the material from which other strontium compounds are produced. No other important compounds are produced directly from the ore. The only other strontium compound that is consumed in significant quantities is $Sr(NO_3)_2$.

ALGERIA

Celestite is mined in Algeria from a surface deposit near Beni Mansour. Estimated reserves are more than 1 million st. The deposit is mined by Enterprise des Produits Nonferreux et des Substances Utiles (ENOF) and is controlled by L'Enterprise Nationale de Developpement Minière (Edemines), a division of Société Nationale de Recherches et d'Exploitations Minières (SONAREM).

No strontium has been exported in recent years, but up to 4,000 st/yr has been exported in the past to Soviet bloc nations and the Federal Republic of Germany. Although the celestite is relatively low in grade, only about 70% $SrSO_4$, it is low in barite, silicate, gypsum, and iron, making it possible to concentrate the ore to acceptable levels using only gravity separation. The deposit has not been fully exploited, but there is interest in further development (*36*).

ARGENTINA

Celestite mining is operated by the Argentine Mining Union at the San Juan Mine in the Mendoza Province. Celestite has also been identified at the Maria Del Carmen and Don Luis Mines, Mendoza Province, and the Rayoso, Julio, Cerro Partido, and Llao Llao Mines, Neuquen Province. It is unlikely that production is carried out on a regular basis at any of these mines. Production from the San Juan Mine was reported at 1,249 st in 1986, the most recent year for which information is available. Almost 60% of this material was exported to Brazil (*38*).

AUSTRALIA

Celestite deposits in South Australia were discovered in 1941 but were exploited for only a very short time (*32*). Recently, Status Minerals NL has begun exploration of other deposits in the desert region of the South Australian Great Artesian Basin. Surface deposits have been identified with over 90% $SrSO_4$. Once the deposit has been delineated, funding for development will be sought through an Australian stock exchange listing (*18*).

CANADA

Canada has produced celestite ore in the past from the McRae deposit, also known as the old Kaiser Celestite Mining Ltd. mine. It is located at Enon, Cape Breton County,

Nova Scotia. Mineral rights are now owned by Timminco Metals, a division of Timminco Ltd. of Toronto. Known reserves are over 1 million st of celestite; grades range from 60% to 65% $SrSO_4$. Reopening the mine is currently being considered, but the low grade of the ore makes economic feasibility questionable. Other strontium deposits have been identified in British Columbia, Newfoundland, and Ontario (*7*), but none are as significant as the deposit in Nova Scotia.

Compounds

Timminco Metals is the largest producer of strontium metal in the world and the only producer of strontium metal in North America. A new facility has recently been completed in Westmeath, Ontario, which increased the potential strontium output by over 40% (*34*). The strontium production facilities in Westmeath and the old facilities in Haley, Ontario, produce strontium metal by the aluminothermic reduction of SrO as discussed previously.

CHINA

Mining

Celestite is currently mined in China almost exclusively for domestic consumption. A new ore dressing facility with a capacity of 11,000 st/yr is located at the Nanjing Mine in the Jiang Su Province. The Nanjing deposit is reported to be high grade and close enough to the surface for open pit mining (*37*).

Compounds

Import data indicate that strontium chemical plants must exist, but no specific details are available. Japan imports $SrCO_3$ from China, and $SrCO_3$ from China has also been recorded in the United States.

CYPRUS

Celestite mining began in Cyprus in 1985 at Vassliko, near Limassol, in southern Cyprus. The mine is operated by Hellenic Mining Co. Ltd. The ore averages about 54% $SrSO_4$ and must be concentrated to make it marketable. The ore is beneficiated through a flotation process to reach 94% $SrSO_4$. The reserves have been determined to be 220,000 st of celestite (*13*, *22*).

FEDERAL REPUBLIC OF GERMANY

Kali-Chemie AG of Hannover produces $SrCO_3$ from imported celestite at its plant at Bad Hoenningen. The major Western European producer uses the black ash method in the recently expanded production facilities. Plant capacity is estimated to be 16,500 st/yr. Kali-Chemie imports most of its celestite from Spain and Turkey; it exports 80% to 90% of the production, most of which goes to the United States and the Republic of Korea.

Kali-Chemie also produces strontium hydroxide and strontium nitrate. The nitrate is produced by its Italian subsidiary, Societa Bario e Derivati SpA, in Massa (*12*, p. 25).

INDIA

Atul Mining Works is believed to mine strontianite, from a mine near Bhawanimandi in Rajasthan, but no reports of production are available (*28*, p. 9). During the 1940's, a significant celestite deposit was reported in the Trichinopoly district containing 500,000 to 1,000,000 st of 96% celestite. There are no indications that the deposit has been developed (*11*).

IRAN

One of the world's largest celestite deposits is located in the northwestern part of the Dasht-e-Kavir salt desert. The deposit is mined by Iran Strontium Co., a subsidiary of Cherkate Sahami Sanati Va Maadani Irani (Simiran). Average $SrSO_4$ values for the deposit are reported at over 91%, but there are unfavorably high levels of barium sulfate ($BaSO_4$) and calcium sulfate ($CaSO_4$). Proven reserves total 2 million st of celestite, 475,000 st of which have no overburden (*30*). Most of the celestite produced from this deposit is believed to go to the U.S.S.R.

ITALY

Mining

Mining is done by Minera Chimica Farnesiana SpA in Tarquinia, near Rome. Most production of this 75% $SrSO_4$ and 5% $BaSO_4$ product is sold domestically (*26*). Production capacity at the mine was recently expanded to 8,000 st/yr, but production has not come close to this level. Some of the processed ore has been exported to the U.S.S.R. (*41*) Other deposits exist in central Sicily, although none are presently being mined.

Compounds

$Sr(NO_3)_2$ is manufactured by Societa Bario e Derivati, a subsidiary of Kali-Chemie AG of the Federal Republic of Germany, at Massa. Production and capacity figures are not available, but it is known that most of the production goes to the United States (*28*, p. 35).

JAPAN

Japan is the largest consumer of $SrCO_3$ in the world, mostly due to its large television and electronics industry. No celestite is mined in Japan, but four companies produce $SrCO_3$ from imported celestite.

Honjo Chemical Corp. operates a production facility for 20,000 st/yr of carbonate at Neyagawa in Osaka using celestite from Spain and China. Sakai Chemical Industry Co. Ltd. also produces $SrCO_3$ via the black ash method in Osaka at a 13,000-st/yr plant, using Chinese, Mexican, and Spanish celestite. Japan Special Chemicals (Nihon Tokushu Kasei) and Dowa Chemicals also produce $SrCO_3$, but on a much smaller scale; the total capacity for both companies is only about 1,200 st/yr. Both companies use celestite from Spain (*42*).

The total Japanese capacity of about 34,000 st/yr is only sufficient to supply half of the estimated domestic demand;

additional $SrCO_3$ is imported from the Federal Republic of Germany and China (*28*, pp. 27-28).

MADAGASCAR

Celestite production has been reported in Madagascar, but no details are known. Exports of extremely small quantities to the United States have been reported.

MEXICO

Mining

Mexico is one of the world's three largest producers of celestite. The most recent Directory of Mexican Non-Metallic Minerals Trust lists 11 companies currently mining celestite. Compañía Minera La Valenciana SA (CMV) mines celestite from the San Agustín deposit near Torreón, Compañía Minera Ocampo SA mines a deposit near Saltillo in Nuevo Leon State and has some small production in Hidalgo, Aguascalientes, and Chihuahua States. Reserves of the San Agustín Mine alone have been estimated at over 800,000 tons. Sales y Oxidos (SYOSA), which is 49% owned by Church and Dwight of Princeton, NY, mines west of Monterrey. Other small operations occur in Coahuila, Aguascalientes, Chihuahua, and Nuevo Leon.

Mexican celestite is primarily high grade with only hand sorting required to achieve at least 92% $SrSO_4$ with low barium content. Abandoned mines and easily identified deposits that have not yet been developed are common throughout a large area in northern Mexico. These deposits have not been extensively explored, but reserves are believed to be vast (*40*).

Compounds

$SrCO_3$ production has been a recent development in Mexico. Because of the huge celestite resources in the country, this is a very attractive location for additional production facilities.

After FMC Corp., a major U.S. $SrCO_3$ and $Sr(NO_3)_2$ producer, closed its California plant in 1984, Cia Minera La Valenciana SA brought the $SrCO_3$ processing equipment. The plant, which utilized the soda ash method of carbonate production and was converted to the black ash method, was relocated to Torreón in Coahuila State, near where the company operates a mine. The plant capacity is 13,000 st/yr. Shipments from the plant, targeted for the television and electronics industry in the Far East, commenced in May 1987.

SYOSA recently expanded $SrCO_3$ capacity at its plant near Monterrey to 8,000 st/yr. SYOSA, which produces carbonate by the black ash method from celestite it mines nearby, is marketing its production in the United States (*28*, p. 29).

PAKISTAN

All mines in Pakistan are the property of provincial governments and are operated by private companies for these governments. Recent celestite production figures have been reported for two active mines, one near Dawood Khail and one near Karachi (*39*). Tawakkal Mineral Exports Corp. recovers celestite from these mines in the Dadu District of Sind Province. No beneficiation is necessary to produce 94% $SrSO_4$. Reserves of celestite have not been quantified at this location (*14*). Other deposits with 550,000 tons of reported reserves have been identified in the Punjab Province (*28*, p. 13).

REPUBLIC OF KOREA

Celestite deposits have not been identified in Korea, but its growing electronics and television industry has prompted two European companies to enter joint ventures with Korean firms to build production facilities for $SrCO_3$ and $BaCO_3$ in that country. Kali-Chemie has announced a joint venture with Samsung Corning Ltd., Korea, to form Daehan Specialty Chemicals Co. Ltd. to build a $SrCO_3$ and $BaCO_3$ plant on the Korean coast. The plant is to have a production capacity of 33,000 to 44,000 st/yr of $SrCO_3$ and $BaCO_3$ combined, which will be targeted for the growing television industry in that country. The black ash method will be used.

Kofran Chemical Co., a joint venture between Rhóne-Poulenc S.A., France, and Oriental Chemical Industry Ltd., Korea, has been formed to build a $SrCO_3$ and $BaCO_3$ plant in Inchon. Production of 22,000 st/yr of the two carbonates should be possible. The chemicals produced at this facility will also be targeted for the television industry in the Far East (*19*).

SPAIN

Mining

Spain is one of the largest producers worldwide. Celestite is produced from the Montevive deposit, which is operated by Herederos de Aurelio Fajardo Vilches, with sales and marketing handled by Bruno S.A. Selective mining and hand sorting are all that is necessary to produce ore grades of over 92% $SrSO_4$, although a concentration plant is under construction. Reserves are believed to be at least 2.2 million st. Most Spanish production is exported to Japan, although some remains in Spain and some is exported to the Federal Republic of Germany (*28*, pp. 13-15).

Compounds

$SrCO_3$ and $Sr(NO_3)_2$ are produced by Promotora de Industria del Sur (Proinsur S.A.) at a combined facility near Granada. The plant has a theoretical design capacity of 8,800 st/yr of carbonate, but has never reached this capacity. $SrCO_3$ is produced by the soda ash method. The plant also has a production capacity of about 3,000 st/yr of nitrate, which has not yet been fully utilized (*15*, p. 40). Most Spanish carbonate is consumed in European and Australian markets; about half of the nitrate is exported to the United States (*28*, p. 35).

TURKEY

Turkey competes with Mexico, Spain, and Iran in claiming the world's largest strontium reserves. Celestite is produced by Barit Maden Turk AS from a mine near Sivas. Another mine near Sivas was formerly operated by Bilfer Madencilik AS, which is currently reestablishing old conces-

sions for future celestite mining. Run-of-mine ore is gravity-separated to produce a product with a minimum of 95% $SrSO_4$. Owing to the harsh climate in the region, the mine is only operated from May to October.

Turkey's identified reserves are placed at 600,000 st, with further reserve potential estimated to be greater than 2 million st. Turkish celestite is primarily exported to the Federal Republic of Germany (*20*, p. 14).

UNITED KINGDOM

Celestite deposits, which occur in the Bristol area, are mined by Bristol Minerals Co. Ltd. The ore is crushed, washed, and graded to achieve a product with 95% $SrSO_4$. Reserve estimates range from 110,000 to 550,000 st (*28*, p. 17). This is the one of the few sites where celestite deposits are not in remote locations (*12*, p. 23), and the deposits are being encroached on by large-scale housing developments, limiting their possible exploitation to the near future.

UNITED STATES

Mining

Although there have been no active celestite mines in the United States since 1959, celestite deposits have been identified nationwide. During World War II, domestic mining of celestite resources occurred in Texas and California. U.S. celestite mines had at that time been inactive since World War I, with all demand for strontium minerals being met from foreign sources.

Deposits were operated in 1944 near Blanket, Brown County, TX, in Nolan County, TX, in the Fish Mountains in Imperial County, CA, and near Ludlow, CA (*16*). At that time the major use for strontium chemicals was for pyrotechnic applications such as signal flares and tracer bullets required for the military effort. Immediately following the war, this demand disappeared, causing domestic production to decrease quickly and eventually taper off to nothing.

Resources in the United States have been estimated at 3.5 million st, with an identified reserve base of 1.5 million st. The reserve figure includes material containing no more than 60% $SrSO_4$, which is much too low grade to meet today's rigid specifications. In addition to deposits operated in the early 1940's, celestite has been discovered in Arizona, Arkansas, Kentucky, Michigan, Missouri, New York, Ohio, Pennsylvania, Tennessee, Utah, and Washington (*29*).

Compounds

Chemical Products Corp. (CPC) of Cartersville, GA, is the only company that produces strontium compounds from celestite. The majority of the celestite CPC uses is from the Mexican deposits. CPC utilizes the black ash method of $SrCO_3$ production at its facility, which is estimated to have an annual production capacity of 11,000 st (*28*, p. 26). CPC purchased the $Sr(NO_3)_2$ production facilities from FMC Corp. in Modesto, CA, when that company discontinued production in 1984. The company moved the equipment to Cartersville and now produces $Sr(NO_3)_2$.

Several U.S. companies produce strontium compounds from $SrCO_3$. Mallinkrodt Inc., St. Louis, MO, produces SrCl, and Mineral Pigments Corp., Beltsville, MD, produces $SrCrC_4$. A few other companies produce downstream strontium compounds, but on a very small scale.

U.S.S.R.

Mining

Very little is known about Soviet production of strontium minerals. Deposits are known in the Karakum Desert on the Zaunguz Plateau; in Permian rock near Bashkir; in the caprocks of the Romy and Isachkov salt domes; in the Pinega area, Archangel province; in Yakutsk, eastern Siberia; and in Turkestan from eastern Fergana to the Caspian Sea, and from southeastern Bucharia to the Sea of Aral. Reserves are believed to be very large, but the ore grade is probably not high (*21*).

Compounds

No details are available concerning the production of $SrCO_3$ in the U.S.S.R. except that there is production, probably from both domestic celestite and imports from Iran and Turkey.

SECONDARY SUPPLY

There is essentially no secondary supply for strontium or strontium compounds. The only instances of recycling occur in television picture tube plants when an imperfect tube is produced. The faceplate of the tube is removed and returned to the glass furnace to be remelted.

SUPPLY-DEMAND RELATIONSHIPS

World production of strontium minerals has increased steadily in the past 10 yr, as demand for strontium for color televisions and ferrite magnets for the electronics industry has grown. Mineral production in market economy countries expanded more than 80% between 1977 and 1986, thus increasing supply for the increased demand. Production increases reflect trends to greater production from traditional sources as well as recent initiation of production in a new facility in Cyprus. The United States has traditionally been the leading consumer of strontium minerals and compounds, but Japan has taken the lead in recent years.

Twelve countries including the People's Republic of China and the U.S.S.R. currently produce strontium minerals, primarily celestite. Mexico, Spain, and Turkey are

the three largest suppliers of celestite to world markets. Mexico exports the majority of its celestite to the United States, Spain exports most of its celestite to Japan and the Federal Republic of Germany, and Turkey exports most of its celestite to the Federal Republic of Germany and the U.S.S.R. The United States depends entirely on imported minerals, most of which come from Mexico. There has been no U.S. celestite mining for about 30 yr.

In recent years U.S. imports of strontium compounds have been rising owing to the increased demand from the television and electronics industries, and the decreased supply due to the closing of the FMC plant in Modesto, CA, in 1985. In 1987, the United States imported about 18,600 st of celestite and about 5,500 st of strontium compounds. Georgia is the only State in which $SrCO_3$ is produced, and because there is only one company in production, output is withheld from publication to protect company proprietary data.

TABLE 5.—Strontium supply-demand relationships, 1977-87
(Short tons contained strontium)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987[e]
					WORLD PRODUCTION						
Mine production:											
United States	0	0	0	0	0	0	0	0	0	0	0
Rest of world (celestite)	44,871	44,746	46,664	46,433	60,917	68,386	74,057	68,516	82,737	72,864	86,883
Total	44,871	44,746	46,664	46,433	60,917	68,386	74,057	68,516	82,737	72,864	86,883
					COMPONENTS AND DISTRIBUTION OF U.S. SUPPLY						
Shipments of Government stockpile excesses (celestite)	0	0	440	0	0	0	0	0	0	0	0
Imports (celestite and compounds)	19,800	20,400	22,400	18,800	24,300	15,600	22,400	24,000	20,500	19,200	24,100
Industry stocks, Jan. 1 (celestite)	4,000	4,800	4,300	6,900	5,600	7,700	6,300	5,900	6,600	8,600	7,100
Total U.S. supply	23,800	25,200	27,140	25,700	29,900	23,300	28,700	29,900	27,100	27,800	31,200
Distribution of U.S. supply:											
Exports (celestite and compounds)	NA	NA	NA	NA	3,000	300	NA	NA	19	750	1,750
Industry stocks, Dec. 31 (celestite)	4,800	4,300	5,040	5,600	7,700	6,300	5,900	6,600	8,600	7,100	9,800
Industrial demand (celestite and compounds)	19,000	20,900	22,100	20,100	19,200	16,700	22,800	23,300	[1]18,500	[1]20,000	[1]19,700
					U.S. DEMAND PATTERN[e]						
Television picture tube glass	12,300	13,700	14,000	13,500	12,400	10,300	14,600	12,300	9,600	12,000	12,400
Pyrotechnic materials	3,000	3,600	3,600	2,400	2,800	2,600	3,200	3,300	2,800	2,000	2,000
Ferrite magnets	900	1,000	1,100	1,000	1,000	1,200	1,100	2,600	2,200	2,200	2,200
Ceramics and glass	200	250	300	100	100	100	200	200	100	100	100
Electrolytic production of zinc	1,300	1,500	2,000	1,000	800	500	900	1,400	1,100	1,100	1,000
Pigments	220	250	200	800	800	700	700	1,900	1,500	1,400	1,000
Other	1,080	600	900	1,300	1,300	1,300	2,100	1,600	1,200	1,200	1,000
Total demand (celestite and compounds)	19,000	20,900	22,100	20,100	19,200	16,700	22,800	23,300	18,500	20,000	19,700

[e] Estimated. NA Not available.
[1] Data may not add to total shown owing to independent rounding.

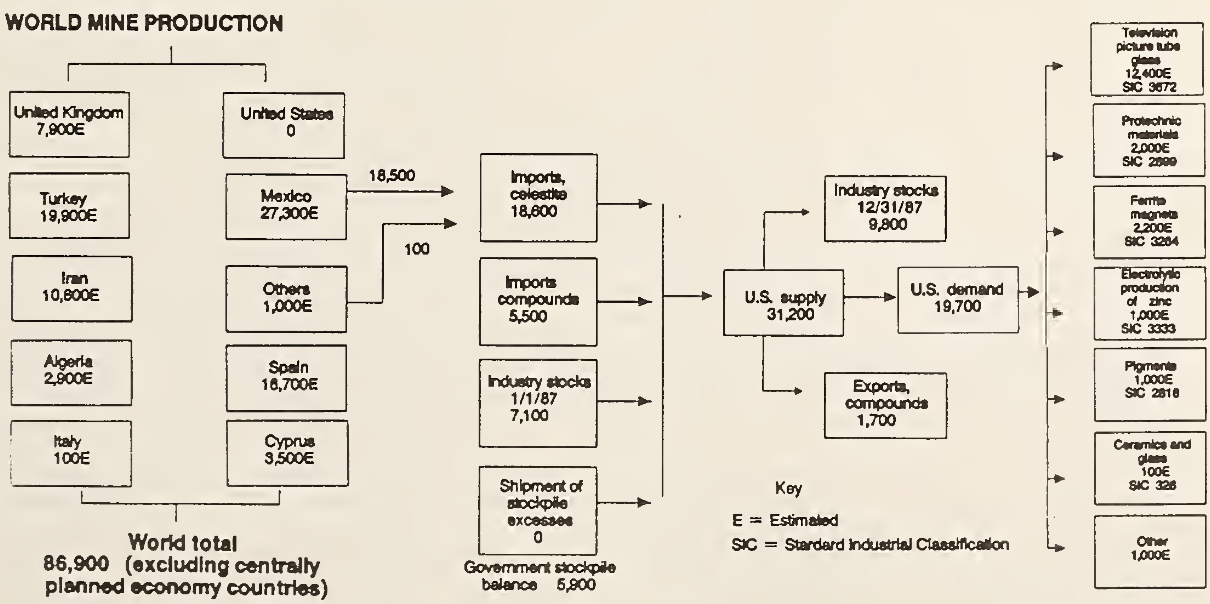

FIGURE 3.—Supply-demand relationships for strontium, 1987. All figures in short tons of strontium.

TABLE 6.—U.S. imports for consumption of strontium minerals, 1977-87

Country	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
QUANTITY (SHORT TONS)											
Canada	0	0	183	0	0	74	0	0	0	0	0
China	0	0	0	0	0	0	0	0	0	348	297
Madagascar	0	0	0	0	0	0	(1)	(1)	0	0	0
Mexico	42,968	41,289	43,406	37,817	48,046	32,992	47,007	46,873	37,552	30,904	42,172
Spain	0	0	0	829	1,653	9	2,789	1,978	0	1,983	0
Sweden	(1)	0	0	0	0	0	0	0	0	0	0
Turkey	0	0	367	0	0	0	0	0	0	0	0
United Kingdom	18	0	0	0	0	0	0	0	0	0	0
U.S.S.R.	0	0	0	(1)	0	0	0	0	0	0	0
Total	42,986	41,289	43,956	38,646	49,699	33,075	49,796	48,851	37,552	33,235	42,469
VALUE (THOUSANDS)											
Canada	0	0	$8	0	0	$7	0	0	0	0	0
China	0	0	0	0	0	0	0	0	0	$64	$38
Madagascar	0	0	0	0	0	0	$1	$1	0	0	0
Mexico	$1,913	$1,885	2,304	$2,086	$2,937	2,042	3,080	3,940	$3,321	$2,991	$3,636
Spain	0	0	0	60	269	8	626	352	0	342	0
Sweden	1	0	0	0	0	0	0	0	0	0	0
Turkey	0	0	22	0	0	0	0	0	0	0	0
United Kingdom	1	0	0	0	0	0	0	0	0	0	0
U.S.S.R.	0	0	0	1	0	0	0	0	0	0	0
Total	1,915	1,885	2,334	2,147	3,206	2,057	3,707	4,293	3,321	3,397	3,674

[1] Less than 1 unit.

Source: Bureau of the Census.

U.S. supply-demand relationships are summarized in table 5, and 1987 relationships are illustrated in figure 3. U.S. demand for strontium products in 1987 was estimated at 19,100 st; television picture tubes comprised about 63% of consumption, ferrite magnets 11%; pyrotechnic material 10%; and other uses 16%. U.S. demand was approximately 25% of world strontium production. Japan and the Federal Republic of Germany also account for large shares of world demand for strontium. Statistics for production of $SrCO_3$ are not available for most countries, because of the small size of the industry when compared to other commodities.

U.S. imports of strontium minerals and compounds have fluctuated, reflecting changes in the structure of the domestic industry. The closing of the FMC facility in 1985 caused a large drop in the amount of imported celestite, but since then CPC has expanded production of $SrCO_3$ and commenced production of $Sr(NO_3)_2$. Owing to these factors, imports of Mexican celestite are approaching the levels reached before the FMC shutdown. Imports of other strontium compounds have also increased in response to the lost production capacity from the FMC closing. Tables 6-8 show the trend in imports of strontium minerals and compounds since 1977.

TABLE 7.—U.S. imports for consumption of strontium metal, unwrought, 1980-87
(All imports are from Canada except as indicated by footnote 1)

Year	Pounds	Value
1980	38,651	$334,653
1981	33,382	330,571
1982	14,633	137,070
1983	1,991	22,790
1984	1,424	17,980
1985	9,052	86,160
1986	50,928	467,759
1987[1]	82,735	749,026

[1] Includes 11 pounds valued at $1,220 from the United Kingdom.

Source: Bureau of the Census.

RESEARCH AND DEVELOPMENT

The only application for strontium in which active, well-publicized research has occurred recently is in superconductors. Superconducting properties were identified in SrO at the National Bureau of Standards in 1964 (*5*), but not until the discovery of high-temperature superconductors in early 1987 did more extensive research continue. The recent work with high-temperature materials has attracted attention from the media and aroused interest in developing these materials, which hold so much promise.

Research being conducted at the University of Houston and the National Research Institute for Metals in Tsukuba, Japan, has identified a material containing strontium that exhibits superconducting properties at a temperature higher than that of liquid nitrogen. Superconducting materials that are currently being used must be cooled with much more expensive liquid helium to reach a temperature low enough to cause superconductivity (*44*). Although this research holds promise, many problems must be overcome for superconductivity to achieve widespread use.

The earliest high-temperature materials are extremely brittle and have a low current-carrying capacity. To apply these materials in a practical fashion, they must be flexible enough to form wires that can be wound into coils, and current-carrying capacity must increase dramatically. Choice of substrate material, the material onto which the superconductor is applied, is a critical factor also. During processing, the superconductor must maintain its crystal structure and not diffuse with the substrate. Strontium titanate is one of the preferred substrate materials, but it is very expensive and some interdiffusion occurs.

The superconducting materials containing strontium exhibit improved characteristics over the earlier compounds containing barium, but further research has identified other materials that appear even more promising. As research progresses, new materials will be formulated and discarded in quicker succession. It may be years before the optimum material composition for these superconductors is determined, and strontium materials may be long rejected for such use by them (*24*).

TABLE 8.-U.S. Imports for consumption of strontium coupounds, 1977-87

Country	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
				STRONTIUM CARBONATE, NOT PRECIPITATED							
Quantity, lb:											
Canada	0	0	1,500	0	0	0	0	436	0	0	0
Germany, Federal Republic of	39,802	39,683	79,366	0	11,023	0	39,683	39,683	0	39,682	0
Mexico	0	0	0	0	0	0	0	84,000	186,384	0	44,092
Spain	0	0	0	0	0	0	0	39,683	0	0	34,172
United Kingdom	0	0	0	0	58	34	38	0	0	0	0
Total	39,802	39,683	80,866	0	11,081	34	39,721	163,802	186,384	39,682	78,264
Value:											
Canada	0	0	$500	0	0	0	0	$345	0	0	0
Germany, Federal Republic of	$6,388	$6,233	14,765	0	$2,571	0	$11,047	11,233	0	$11,663	0
Mexico	0	0	0	0	0	0	0	23,880	$51,256	0	$10,948
Spain	0	0	0	0	0	0	0	9,423	0	0	1,875
United Kingdom	0	0	0	0	2,275	$1,745	3,764	0	0	0	0
Total	6,388	6,233	15,265	0	4,846	1,745	14,811	44,881	51,256	11,663	12,823
				STRONTIUM CARBONATE, PRECIPITATED							
Quantity, lb:											
Canada	131,484	12,139	14,294	317,462	0	0	0	158,733	119,049	0	0
China	62,059	0	2,205	0	0	0	0	829,547	37,478	0	0
France	0	0	0	0	1,596,117	0	0	0	0	0	0
Germany, Federal Republic of	2,292,716	6,521,008	7,682,615	4,118,201	4,485,345	2,864,676	938,007	5,586,138	9,676,889	8,208,672	10,120,618
Japan	0	0	0	0	0	0	0	0	0	0	11,670
Mexico	75,527	0	0	0	0	0	0	354,200	244,100	3,739,467	4,263,566
Netherlands	2,557	0	0	0	39,682	3,120	0	0	0	0	0
United Kingdom	0	5	1	2	3	12	5,143	0	0	27	41,798
Total	2,564,343	6,533,152	7,699,115	4,435,665	6,121,147	2,867,808	943,150	6,928,618	10,077,516	11,948,166	14,437,652
Value:											
Canada	$24,850	$6,144	$7,147	$70,560	0	0	0	$66,935	$35,169	0	0
China	12,481	0	565	0	0	0	0	253,331	11,003	0	0
France	0	0	0	0	$365,442	0	0	0	0	0	0
Germany, Federal Republic of	364,387	1,190,818	1,498,128	920,465	1,117,482	$797,280	$290,620	1,577,834	2,955,649	$2,247,425	$3,247,927
Japan	0	0	0	0	0	0	0	0	0	0	8,982
Mexico	13,035	0	0	0	0	0	0	130,219	64,800	931,557	1,139,916
Netherlands	663	0	0	0	9,826	3,010	0	0	0	0	0
United Kingdom	0	528	399	364	886	1,864	8,007	0	0	2,536	27,321
Total	415,416	1,197,490	1,506,239	991,389	1,493,636	802,154	298,627	2,028,319	3,066,621	3,181,518	4,424,146
				STRONTIUM CHROMATE							
Quantity, lb:											
Belgium	0	0	0	0	0	0	0	5,291	154,102	101,853	21,826
Canada	553,800	623,410	420,370	483,525	867,750	462,815	53,010	0	0	0	29,765
France	0	41,667	0	0	6,070	27,006	235,284	222,665	207,154	41,005	160,932
Germany, Federal Republic of	661	0	39,683	0	0	14,318	3,337	13,228	260,541	59,524	39,684
Italy	0	0	0	0	0	0	0	0	17,637	0	0
Poland	0	0	0	0	0	35,274	0	0	0	0	0
Spain	0	0	0	0	0	0	28,660	147,647	187,714	46,297	0
United Kingdom	0	0	0	0	0	228	10,155	4,698	0	453	10,400
Total	554,461	665,077	460,053	483,525	873,820	539,641	330,446	393,529	827,148	249,132	262,607
Value:											
Belgium	0	0	0	0	0	0	0	$5,941	$149,580	$266,510	$26,628
Canada	$461,019	$591,987	$435,630	$525,411	$1,041,755	$634,893	$59,131	0	0	0	41,509
France	0	18,824	0	0	7,939	27,714	240,994	224,149	231,333	49,275	198,080
Germany, Federal Republic of	1,561	0	7,485	0	0	10,427	5,588	19,340	244,541	53,017	47,305
Italy	0	0	0	0	0	0	0	0	19,456	0	0
Poland	0	0	0	0	0	21,199	0	0	0	0	0
Spain	0	0	0	0	0	0	31,034	161,879	212,206	53,592	0
United Kingdom	0	0	0	0	0	2,073	10,788	13,574	0	2,432	11,218
Total	462,580	610,811	443,115	525,411	1,049,694	696,306	347,535	424,883	857,116	424,826	324,740
				STRONTIUM NITRATE							
Quantity, lb:											
Canada	80,000	0	425	0	0	0	0	0	0	0	0
France	0	0	220	0	0	0	0	0	0	0	0
Germany, Federal Republic of	200,932	158,731	1,872	0	2,334	1,228	0	0	882	1,320	1,357
Ireland	0	0	0	29	0	0	0	0	0	0	0
Italy	0	513,672	3,085,558	816,363	2,124,681	363,200	815,414	970,517	935,633	975,865	1,183,671
Mexico	0	0	0	0	0	0	0	0	0	0	2,205
Spain	0	0	0	0	0	41,887	45,194	865,619	2,427,631	2,103,227	481,708
Switzerland	0	0	0	0	0	0	0	0	0	88,184	0
United Kingdom	0	0	0	0	5	13	0	0	0	79,971	0
Total	280,932	672,403	3,088,075	816,392	2,127,020	406,328	860,608	1,836,136	3,364,146	3,248,567	1,668,941
Value:											
Canada	$18,400	0	$391	0	0	0	0	0	0	0	0
France	0	0	533	0	0	0	0	0	0	0	0
Germany, Federal Republic of	61,319	$49,591	4,326	0	$7,920	$5,774	0	0	$3,014	$6,389	$8,675
Ireland	0	0	0	$628	0	0	0	0	0	0	0
Italy	0	128,278	792,467	269,100	766,236	136,160	$351,230	$417,918	371,571	398,385	512,396
Mexico	0	0	0	0	0	0	0	0	0	0	2,000
Spain	0	0	0	0	0	14,007	15,622	325,233	966,496	816,793	244,859
Switzerland	0	0	0	0	0	0	0	0	0	41,762	0
United Kingdom	0	0	0	0	886	874	0	0	0	35,841	0
Total	79,719	177,869	797,717	269,728	775,042	156,815	366,852	743,151	1,341,081	1,299,170	767,930
				STRONTIUM COMPOUNDS, OTHER							
Quantity, lb:											
Belgium	0	0	0	0	0	0	0	441	44,754	407,407	0
Canada	0	30,824	22,121	0	0	0	0	0	65,150	0	3,429
China	0	0	0	0	0	0	0	0	0	0	37,478
France	882	0	0	0	0	4,000	0	0	0	110	0
Germany, Federal Republic of	46,495	199,387	50,484	82,460	51,749	8,973	18,963	22,391	58,863	792,582	2,709,526
Hong Kong	0	960	0	0	0	0	0	0	0	0	0
Italy	0	79,366	276,899	0	0	0	0	0	0	0	0
Japan	31,262	44,383	44,489	45,205	68,342	44,092	24,246	157,364	261,795	247,489	546,742
Netherlands	0	0	0	0	0	0	366	7,726	0	66	694
Spain	0	0	0	0	0	0	39,683	0	0	0	0
United Kingdom	1	22	3	577	1,705	771	16,983	0	22,157	6,342	31,838
Total	78,640	354,942	393,996	128,242	121,796	57,836	100,241	187,922	452,719	1,453,996	3,329,707
Value:											
Belgium	0	0	0	0	0	0	0	$390	$45,026	$43,407	0
Canada	0	$1,599	$1,480	0	0	0	0	0	5,693	0	$29,409
China	0	0	0	0	0	0	0	0	0	0	4,161
France	$2,498	0	0	0	0	$5,040	0	0	0	1,439	0
Germany, Federal Republic of	39,663	97,380	69,915	$66,421	$16,501	16,523	$21,132	22,913	55,379	244,367	179,372
Hong Kong	0	475	0	0	0	0	0	0	0	0	0
Italy	0	17,631	65,419	0	0	0	0	0	0	0	0
Japan	13,961	22,295	28,544	32,922	49,475	32,693	13,698	109,954	175,069	180,311	1,260,403
Netherlands	0	0	0	0	0	0	4,453	11,598	0	1,237	5,575
Spain	0	0	0	0	0	0	14,028	0	0	0	0
United Kingdom	326	2,443	540	1,783	10,484	1,273	21,411	0	29,695	14,857	54,892
Total	56,448	141,823	165,898	101,126	76,460	55,529	74,722	144,855	310,862	485,618	1,533,812

Source: Bureau of the Census.

LEGISLATION AND GOVERNMENT PROGRAMS

Tariffs

Tariffs levied against specific imported strontium compounds are listed in table 9. An ad valorem tariff is calculated as a percentage of the value of the goods passed through customs. Most Favored Nation treatment provides to all trading partners the same customs and tariff treatment given to all countries that fall into that category.

The United States applies this provision to all trading partners except those specifically excluded by law. Countries that are legally excluded from Most Favored Nation status are Afghanistan, Albania, Bulgaria, Cuba, Czechoslovakia, Estonia, the German Democratic Republic, Kampuchea, Laos, Latvia, Lithuania, Mongolia, North Korea, Poland, the U.S.S.R., and Vietnam.

The International Trade Commission has investigated allegations pertaining to the dumping of $Sr(NO_3)_2$ from Italy twice in the last 10 yr. The Commission unanimously determined in 1980 that reasonable indications existed that U.S. industry was materially injured or threatened by injury, by reason of imports of strontium nitrate from Italy. These imports were deemed to be sold in the United States at less than fair value (*8*). An antidumping duty order was instituted at that time; the order was revoked in 1984 (*9*).

TABLE 9.—Applicable tariffs for strontium minerals and compounds, January 1, 1987

Item	TSUS No.	Most Favored Nation (MFN)	Non-MFN
Compounds:			
Carbonate:			
Not precipitated	421.70	Free	Free.
Precipitated	421.72	4.2% ad val.	25% ad val.
Nitrate	421.74	4.2% ad val.	25% ad val.
Oxide	421.76	4.2% ad val.	25% ad val.
Minerals:			
Celestite	421.82	Free	Free.
Other	421.84	3.7% ad val.	25% ad val.
Other	421.86	3.7% ad val.	25% ad val.

ad val. Ad valorem.

A similar allegation was investigated in 1987. The Commission determined that no dumping occurred during the period in question, June 1, 1985, to May 31, 1986. No antidumping duties were assessed (*10*).

Depletion Allowance

Depletion allowance is a proportion of a company's income derived from mining or oil production that is considered to be a return of capital not subject to income tax. Depletion allowance is 22% for domestic strontium and 14% for foreign strontium.

Government Stockpile

During World War II, demand for strontium nitrate and other pyrotechnic chemicals expanded dramatically. At that time almost all celestite was imported from England and Germany. The supply from Germany was cut off long before the United States entered the war, and the supply from England was not very reliable owing to shipping problems associated with the war. For this reason exploration began in Mexico, and recommendations were made to amass a Government stockpile of the material necessary for the war effort.

When the stockpile was initiated in 1942, the $SrSO_4$ content of the celestite was specified at 92%, with a maximum of 4% each of $BaSO_4$ and $CaSO_4$. The most recent specifications issued in September 1960, required the material to contain at least 95% $SrSO_4$ with less than 1.5% $CaSO_4$ and less than 2% $BaSO_4$. In 1963 a stockpile of celestite was determined to be unnecessary, and the General Services Administration began selling stockpile-grade as well as nonstockpile-grade celestite. In 1974 the last of the stockpile-grade material was sold.

Since that time there have been virtually no sales of celestite from that remaining in the stockpile. The material is all well below stockpile specifications; all of it contains less than 91% $SrSO_4$ and more than 4% $CaSO_4$, and some contains almost 10% $CaSO_4$. The low grade of the celestite makes it very difficult, if not impossible, to sell.

STRATEGIC FACTORS

Stockpile Status

The National Defense Stockpile currently contains 13,415 st of celestite, all of which has been designated for disposal. The celestite in the stockpile, which is all low grade, has been valued at about $201,000. Under current policy celestite is to be eliminated from the stockpile.

Import Dependence

The United States is dependent on imports of celestite minerals. There is production of strontium compounds in the United States, but the raw materials for strontium production are 100% imported. The source for these minerals is almost exclusively Mexico.

The fact that Mexico is the major U.S. supplier of strontium minerals does not lessen the import dependence, but does indicate that the country's sources are relatively secure. U.S. supplies are less vulnerable than if the source was more distant, or in a country with less friendly status than is the case between the United States and Mexico. Diversification of supply to other low-cost producers could offer some protection against future disruptions of supply. Development of domestic resources would decrease import dependence, but known deposits are not sufficiently large or of high enough quality to warrant such development unless an emergency situation cuts off U.S. supplies of celestite.

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